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It is of interest to explore the possibility of fabricating active and passive device element such as switches, guides, couplers and detectors on or around single mode optical fibers. Such on-line detection and signal processing would be extremely useful for long-range fiber-optic communication. With this in mind, we have explored heterostructure and quantum well devices which can be laterally coupled to fibers, investigated the growth of GaAs and related materials on silica, fibers and sapphire by molecular beam epitaxy, and have demonstrated for the first time the fabrication and performance of active optoelectronic devices on silica fibers. The lateral coupling of light out of fibers into photodiodes has been characterized experimentally. Two novel heterostructure devices have been demonstrated The first is a bipolar phototransistor with a staircase superlattice in the collector in which selective gain is achieved. The other is a photonic switching device made as a vertic directional coupler with a nonlinear MQW coupling medium.

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ABSTRACT CONTINUED

We have demonstrated for the first time direct single-crystal MBE growth of GaAs on sapphire and the properties of optoelectronic devices on silica fibers.

INVESTIGATIONS OF LATERALLY COUPLED ALL OPTICAL SWITCHES AND DETECTORS ON SILICA FIBERS

FINAL REPORT

by

Professor Pallab K. Bhattacharya

February 1990

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SECTION I. INTRODUCTION

The aim of integrated optics is to be able to do as much signal processing as possible directly on the optical signal itself. It is envisaged that a family of optical and electro-optical elements in thin planar form will be used, allowing the assembly of a large number of such devices on a single substrate. It is of interest to explore the possibility of fabricating active and passive device elements such as switches, guides, couplers and detectors on or around single mode optical fibers. Such on-line detection and signal processing would be extremely useful for long-range fiber-optic communication. With this in mind, we have explored heterostructure and quantum well devices which can be laterally coupled to fibers, investigated the growth of GaAs and related materials on silica, fibers and sapphire by molecular beam epitaxy, and have demonstrated for the first time the fabrication and performance of active optoelectronic devices on silica fibers.

SECTION II. SUPERLATTICE DETECTORS AND PHOTOTRANSISTORS AND THEIR LATERAL COUPLING TO OPTICAL FIBER

The properties of $In_{0.24}Ga_{0.76}As/GaAs$ and $GaAs/In_{0.05}G$[illegible]$Al_{0.37}As$ superlattice photodiodes grown by molecular beam epitaxy have been investigated. From the temporal response characteristics, deconvolved rise times $\sim$ 60-100 ps are obtained. The measured responsivities of the photodiodes with dark currents of 5-10 nA at 10 V are $\sim$ 0.4 A/W, which correspond to peak external quantum efficiences of $\sim$ 60%. These results indicate that very high performance photodiodes can be realized with strained layers.

The principle of operation of a novel bipolar transistor with controlled multiplication of one type of carriers has been demonstrated. The ideal device, with a few periods of a staircase superlattice in the base-collector depletion region, has high current outputs at extremely low bias voltages and high current gains. The principle is experimentally demonstrated in a GaAs/AlGaAs/InGaAs phototransistor where three periods of a periodic pseudomorphic structure, in which electrons should predominantly multiply, are included in the collector depletion region. Independent measurements of the electron and hole avalanche multiplication rates, M_n and M_p, in these structures confirm that M_n/M_p and α/β are $\sim$ 2-4, depending on bias voltage. The observed photocurrent characteristics agree reasonably well with Monte Carlo calculations made to simulate the transport of electrons through the collector region. Measured optical gains are as high as 142 in an n-p-n phototransistor with a 2000 Å p-base region.

The most important aspect of the project was related to the coupling of light from optical fibers monolithically into detectors, which would be eventually integrated with other electronic devices. A novel scheme for tapping of signals carried in optical fibers is demonstrated. Lateral holes through the fiber cladding, formed by lithography and chemical etching or laser machining, are filled with a high-index plug to allow access to the guiding region. The fiber is positioned in a groove in the active semiconductor wafer, and the holes are aligned with a row of mesa-type superlattice avalanche photodiodes which detect the optical signal. Optical crosstalk has been characterized. With an etched hole there is clearly significant leakage, but this is reduced to -26.5 dB at a distance of 900 μm away. This results from the large amount of light scattered from the slowly varying profile of the chemically etched side wall. A great improvement is achieved if laser-machined holes with more nearly vertical side walls are used instead. With the scheme presented here, multiple devices all on a single chip can be triggered independently, thus facilitating parallel processing and image processing. Finally, 'on-line' optical signal processing can be accomplished at any point along the length of the fiber, utilizing, for example, bistable devices grown on the chip functioning as logic gates.

SECTION III. GROWTH OF DEVICE-QUALITY GaAs on SiO_x AND SAPPHIRE

We have investigated the molecular beam epitaxial growth and photoluminescence properties of GaAs on SiO_x. It is seen that material with a grain size of 0.6 - 0.8 μm can be grown directly on the dielectric. The properties improve further when the layers are short-term annealed with a halogen lamp. Optimum grain sizes of 1.6 μm are obtained when the as-grown material is annealed at 950°C for 10 s, and very strong luminescence is observed in the same material. Photoconductive detectors made on the overgrown GaAs show large responsivities.

We have achieved the first successful single-crystal growth of GaAs directly on sapphire substrates by molecular beam epitaxy. Successful growth on the <c> and <r> planes was achieved by carefully controlling the growth kinetics in the initial stages of epitaxy. The crystal orientation was determined to be <111> for growth on both the <c> and <r> planes. Double-crystal x-ray and the Lane diffraction patterns independently confirm the single-crystal nature. Low-temperature photoluminescence measurements indicate strong radiative efficiency of the material. The mechanism of such heteroepitaxy has also been investigated and is understood in terms of the crystal structure and bonding configuration.

SECTION IV. ACTIVE OPTOELECTRONIC DEVICES ON SILICA FIBERS

By using molecular beam epitaxy and post-growth annealing techniques, we have successfully made GaAs interdigitated photoconductive detectors on D-shaped silica fibers. The detectors exhibit low-leakage current and internal optical gains of up to 15 are measured. To our knowledge this is the first realization of active III-V optoelectronic devices on fibers and open up the possibility of realizing opto-electronic integration and circuits directly on fibers. The objective is to activate the detectors with light passing through the fibers via suitable grooves. The generated photocurrent can then be amplified and serve as a routing or clocking signal.

With the above objective in mind we have integrated HEMT amplifiers with the photoconductive detectors made on the silica fibers. The detectors deposited by direct molecular beam epitaxy on D-shaped fused silica fibers exhibit dark currents $\sim$ 10-20. These were integrated with pseudomorphic high electron mobility transistors (HEMT) grown on GaAs substrates in which the fibers are embedded. The transistors with 1 μm gate lengths have d.c. transconductances of 350 - 400 mS/mm. This integration is the first demonstration of on-chip parallel processing of signals being transmitted by a fiber. This capability should find immense applications in computing and communications.

SECTION V. NONLINEAR VERTICAL DIRECTIONAL COUPLERS

The performance characteristics of an AlGaAs dual waveguide vertical coupler with a nonlinear GaAs/AlGaAs multiquantum well coupling medium are demonstrated. The structure was grown by molecular beam epitaxy and fabricated by optical lithography and ion-milling. The nonlinear coupling and modulation behavior is identical to that predicted theoretically. The nonlinear index of refraction and critical output power are estimated to be $n_2 = 1.67 \times 10^{-5}$ cm^2/W and $P_c = 170$ W/cm^2, respectively. This device also allows reliable measurement of the nonlinear refractive index for varying quantum well and optical excitation parameters. This work is being extended with other material systems.

INTERACTION WITH U.S. ARMY PERSONNEL

During the period of this contract we have interacted actively with the following scientists on various aspects of the work: Dr. S. DiVita (Fort Monmouth), Drs. M. Tobin, R. Tober and G. Simonis (Harry Diamond Laboratories) and Dr. M. Stroscio (ARO).

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